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ABSTRACT

Half a century before black hole images based on observations were released, physicists used calculations and simulations to depict what they thought the surroundings of black holes would look like. We focus in particular on the framing and reception of a 1978 image by French astrophysicist Jean-Pierre Luminet. This handmade drawing was described as "realistic" even though black hole shadows had not yet been observed. Using his image to convince astronomers of the existence of black holes, Luminet argued for the accuracy of his image by emphasizing the physical effects taken into account in the simulation he used for his drawing and made references to photography in descriptions of it. At the same time, he presented the appearance of light near a black hole, as seen by a distant observer, as "optical distortions." Like Nobel Laureate Roger Penrose, Luminet was a creator of images used in General Relativity who had found inspiration in Dutch artist M. C. Escher's work. But unlike the plays on perspective that Escher was known for, black hole images were not used to confound the beholder or to make the beholder aware of their role as an interpreter of contradictory images. Luminet instead used apparent "optical distortions" to further intuition about black holes. Focusing on what light near a black hole looked like, Luminet explained why his image looked the way it did to communicate the nature of what was invisible.

KEY WORDS: images in science, black holes, physics, astronomy, astrophysics, Event Horizon Telescope, simulations, General Relativity

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Abbreviations: General Relativity, GR; M87, Messier 87; M87*, the object in the center of the galaxy Messier 87 believed to be a black hole

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INTRODUCTION

What does it mean for an image of the surroundings of a black hole to be "realistic"? This question is particularly important now when recent images, such as that shown in figure 1, have come to define black holes to very large and diverse audiences. Two days after the release of the image shown in figure 1, more than a billion people had seen this image of the shadow of a black hole.[1] Made public by the Event Horizon Telescope Collaboration on April 10, 2019, this image was the first depiction of the immediate surroundings of a black hole based on observation. Yet it was not the first important image in the iconography of black holes. Visual representations of black holes based on calculations and simulations had been produced for half a century before the release of this image.[2] Early visual representations of black holes are important

1. Elizabeth Kessler and Peter Galison, "To See the Unseeable," *Aperture* 237 (2019): 75–78; and Peter Galison, "Images scatter into data—Iconoclasm and the Scientific Image" (15 Feb 2021); www. youtube.com/watch? v=feOm6StmwUQ&feature=emb_logo (accessed 18 Feb 2021). On the Event Horizon Telescope, see also Erik Curiel, "Schematizing the Observer and the Epistemic Content of Theories," arXiv preprint: *arXiv:1903.02182* (2019, accessed 21 Oct 2022); Jamee Elder and Juliusz Doboszewski, "Robustness in Large Astrophysical Experiments: The Case of the Event Horizon Telescope Picture of the M87 Black Hole" (in prep.); Peter Galison, "Philosophy of the Shadow," Harvard CMSA (18 Apr 2019); www.youtube.com/watch?v=BofWFoiKARQ (accessed 2 Jan 2021); Galison, *The Edge of All We Know,* documentary feature (Collapsar, Sandbox Films, 2020); Galison, "How do you Photograph a Black Hole?" *MoMA Magazine* (2021); www.moma.org/magazine/articles/563 (accessed 23 Aug 2022); Galison and Jens Kugele, "Future Trading Zones for the Study of Culture: An interview with Peter L. Galison," in vol. 8 of *Futures of the Study of Culture: Interdisciplinary Perspectives, Global Challenges*, ed. Doris Bachmann-Medick, Jens Kugele, and Ansgar Nünning (Berlin/Boston: De Gruyter, 2020), 288–298; Emilie Skulberg, "The Event Horizon as a Vanishing Point: A History of the Image of a Black Hole Shadow From Observation" (PhD dissertation, University of Cambridge, 2021); Galina Weinstein, "Is the EHT Black Hole Experiment a New Experiment in the Guise of an Old Experiment?" *Studies in History and Philosophy of Science* 88 (2021): 41–49; Galina Weinstein, "Coincidence and Reproducibility in the EHT Black Hole Experiment,"*Studies in History and Philosophy of Science Part A* 85 (2021): 63–78.

2. Brendan B. Godfrey, "Mach's Principle, the Kerr Metric, and Black-hole Physics," *Physical Review D* 1, no. 10 (1970): 2721–2725; James M. Bardeen, "Timelike and Null Geodesics in the Kerr Metric," in *Black Holes (Les Astres Occlus),* ed. Cécile DeWitt and Bryce S. DeWitt, vol. 23 (Gordon & Breach, New York, 1973), 215–239; Christopher T. Cunningham, and James M. Bardeen, "The Optical Appearance of a Star Orbiting an Extreme Kerr Black Hole," *The Astrophysical Journal* 183 (1973): 237–264. Luminet's drawing was one of two visualizations based on simulations produced in 1978 (for its publication in a peer-reviewed journal, see Jean-Pierre Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk," *Astronomy & Astrophysics* 75 [1979]: 228–235). The other was a film clip created by Leigh Palmer, Maurice Pryce, and William Unruh at Simon Fraser University. While the clip was shown at several lectures, the

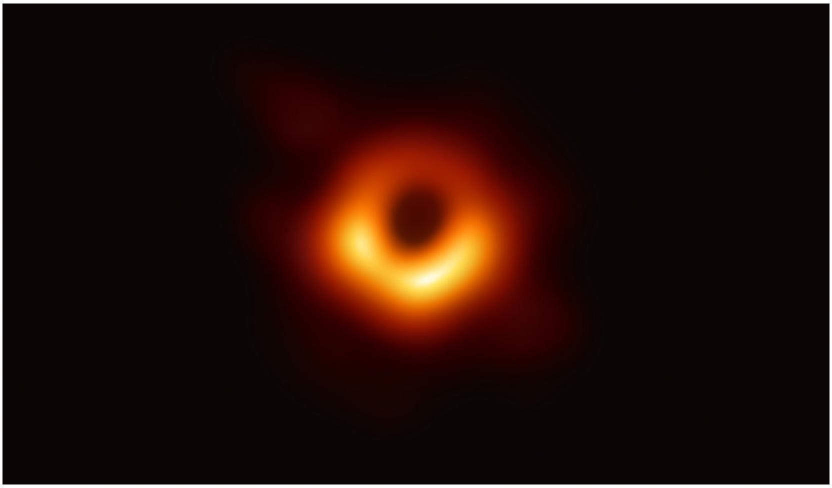

FIGURE 1. The first image of the shadow of a black hole based on observation, April 10, 2019. Credit: Event Horizon Telescope Collaboration. Creative Commons Attribution 4.0 International License.

sources because they show how images were used to introduce audiences to regions of spacetime they had no familiarity with. An important example of this is shown in figure 2, drawn by Jean-Pierre Luminet in 1978. Luminet's drawing was one of the first detailed representations of the surroundings of a black hole, and we focus on this image because of the interesting tensions we found in how it was presented to audiences: Luminet created this drawing to make astronomers believe in the existence of black holes, presented his image as "realistic," and at the same time emphasized its "optical distortions" as a way to explain the nature of black holes.[3]

Before delving into how we approach Luminet's drawing, it is useful to begin with what the image shows. A black hole itself cannot be imaged. But the

work was not published. Sources: Oliver James, Eugénie von Tunzelmann, Paul Franklin, and Kip S. Thorne, "Gravitational Lensing by Spinning Black Holes in Astrophysics, and in the Movie *Interstellar*," *Classical and Quantum Gravity* 32 (2015): 065001, on 2; and Leigh Palmer, e-mail-correspondence with first author, 15 Sep 2017; William Unruh, e-mail-correspondence with the first author, 9 Sep 2017. It should also be noted that trajectories of what was then called light particles around "Schwarzschild's sphere" appeared in a diagram published already in 1921, but the inside of the "sphere" was not considered physically significant. For the diagram, see Max von Laue, *Die Relativitaütstheorie, 2. Bd: Die allgemeine Relativitaütstheorie und Einsteins Lehre von der Schwerkraft* (Braunschweig: Friedr. Vieweg & Son, 1921), 226, and for background on this, Jean Eisenstaedt, *The Curious History of Relativity: How Einstein's Theory of Gravity Was Lost and Found Again* (Princeton, NJ: Princeton University Press, 2006), especially 266–268.

3. Jean-Pierre Luminet, *Black Holes* (Cambridge: Cambridge University Press, 1992), 143.

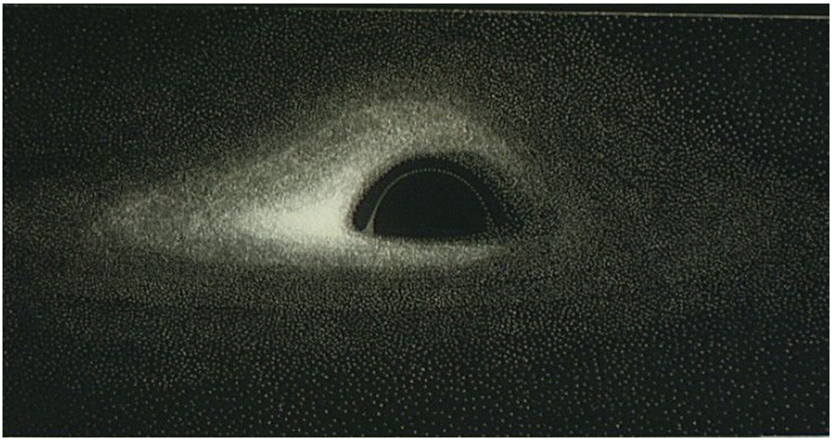

FIGURE 2. Jean-Pierre Luminet, photograph of a drawing (originally black Indian ink on transparent Canson paper), 1978. Courtesy of Jean-Pierre Luminet.

lack of light in this particular region can indicate the presence of an event horizon. In Luminet's drawing, this lack of light was represented by the dark half-disk in the middle of the image. A thin half-circle of light surrounded it. The larger bright area was light from the thin accretion disk (an accretion disk is a disk of matter that can surround astronomical objects such as black holes). The innermost part of the accretion disk began some distance away from the event horizon, as indicated by the dark region forming a larger half-circle around the inner thin light half-circle. On the left-hand side, light from the accretion disk appeared brighter than on the right-hand side (we will return to this).[4] The depiction of the space around a black hole was not easy to interpret: light and darkness looked different than they would in flat spacetime. We will show how Luminet used such effects to communicate the nature of what had not been observed.

We focus on framings of this image to analyze how an extreme region of spacetime was introduced to beholders. *Framing* is used here to refer to the written contextualization of an image. Our aim here is not to contribute to the existing discussion on the nature of text-image interchange, but we do focus on

4. For further descriptions of the image, see Jean-Pierre Luminet, "Black Hole Imaging," conference presentation at the third Black Hole Initiative Conference (23 May 2019); www.youtube.com/watch?v=x1TX8DYM5Ew (accessed 5 Sep 2022); Jean-Pierre Luminet, "40 Years of Black Hole Imaging (1): Early Work 1972–1988," e-LUMINESCIENCES: the blog of Jean-Pierre Luminet (2018). https://blogs.futura-sciences.com/e-luminet/2018/03/07/45-years-black-hole-imaging-1-early-work-1972-1988 (accessed 6 Sep 2022).

how the text was used to present Luminet's drawing in particular ways, and how it was later interpreted.[5] While images within a multitude of scientific disciplines have been studied from a range of perspectives based on the sciences, social sciences, and the humanities, astrophysics has received relatively little attention.[6] Sociological methods, particularly ethnomethodology,

5. William J. T. Mitchell's concepts of *image-text* and *imagetext* have been used as tools to show the importance of close connections between image and text. Whereas *imagetext* refers to the combination between image and text, *image-text* is used to describe the interchange between text and image (see *Picture Theory: Essays on Verbal and Visual Representation* (Chicago: University of Chicago Press, 1994), 89fn9; *The Last Dinosaur Book: The Life and Times of a Cultural Icon* (Chicago: University of Chicago Press, 1998), 51–52; and *Image Science* (Chicago: University of Chicago Press, 2015), chapter 4. See James Elkins, ed., *Visual Literacy* (New York: Routledge, 2008) for further reading on text and image.

6. For introductions to research on images in science, we recommend Albert Cambrosio, Daniel Jacobi, and Peter Keating, "Ehrlich's 'beautiful pictures' and the controversial beginnings of immunological imagery," *Isis* 84 (1993): 662–699; Klaus Hentschel, *Visual Cultures in Science and Technology: A Comparative History* (New York: Oxford University Press, 2014), Michael Lynch and Steve Woolgar, eds., *Representation in Scientific Practice* (Cambridge, MA: MIT Press, 1990); Luc Pauwels, ed., *Visual Cultures of Science: Rethinking Representational Practices in Knowledge Building and Science Communication* (Hanover, NH: Dartmouth College Press, 2006); and Martin Rudwick, "The emergence of a visual language for geological science, 1760–1840," *History of Science* 14 (1976): 149–195. For research on images in astronomy and physics, see Fiona Amery, "Capturing the Northern Lights: Standardizing the Practice of Auroral Photography during the Second International Polar Year, 1932–1933," *Historical Studies in the Natural Sciences* 52, no. 2: 147–189; Charlotte Bigg, "The View from Here, There and Nowhere? Situating the Observer in the Planetarium and in the Solar System," *Early Popular Visual Culture* 15, no. 2 (2017): 204–226; Lorraine Daston and Peter Galison, *Objectivity* (New York: Zone Books, 2007); Connemara Doran, "Instrumentalizing and Visualizing the Cosmic First Light," *Nuncius* 36, no. 1 (2021): 167–192; James Elkins, *Six Stories from the End of Representation: Images in Painting, Photography, Astronomy, Microscopy, Particle Physics, and Quantum Mechanics, 1980–2000* (Stanford, CA: Stanford University Press, 2008); Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997); Klaus Hentschel, *Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching* (New York: Oxford University Press, 2002); David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: University of Chicago Press, 2005); Elizabeth Kessler, "Resolving the Nebulae: The Science and Art of Representing M51," *Studies in History and Philosophy of Science Part A* 38, no. 2 (2007): 477–491; Kessler, *Picturing the Cosmos: Hubble Space Telescope Images and the Astronomical Sublime* (Minneapolis: University of Minnesota Press, 2012); K. Maria D. Lane, *Geographies of Mars* (Chicago: University of Chicago Press, 2010); Lisa Messeri, *Placing Outer Space: An Earthly Ethnography of Other Worlds* (Durham, NC & London: Duke University Press, 2016); Joshua Nall, *News From Mars: Mass Media and the Forging of a New Astronomy, 1860–1910* (Pittsburgh: University of Pittsburgh Press, 2019); Omar Nasim, *Observing by Hand: Sketching the Nebulae in the Nineteenth Century* (Chicago: University of Chicago Press, 2013); Alex Soojung-Kim Pang, "Victorian Observing Practices, Printing Technology, and Representations of the Solar Corona," Part 1, *Journal for the History of Astronomy* 25 (1994): 249–

have been the primary methods used in existing studies of astronomical images.[7] These studies have made valuable and rich contributions to the study of image production, observation, and the nature of collaborations in astronomy and physics. With the focus on the dynamics of research groups and collaborations, however, a close reading of publications is sometimes neglected despite how important they are for how images in science are presented. This paper offers a close reading of the contextualization of Luminet's drawing in publications.

We will show how the drawing was presented by Luminet as showing "optical distortions" and as "realistic," as well as how such images came to be seen not only as realistic but as visual predictions of the image shown in figure 1. The first two sections of the paper address how Luminet's drawing was described as both "distorted" and "realistic." Because of the extremity of the environment of a black hole, light close to it will be lensed. The deflection of light is not an illusion but rather a question of tracing the way light actually travels in a given space.[8] In curved space, the light trajectories would simply be different from those in flat space. However, in his publications, Luminet framed his drawing as depicting "optical distortions" and "optical deformations, due to the deflection of light rays produced by the strong curvature of

274; and Part II, ibid. 26 (1995): 63–75; Pang, "'Stars Should Henceforth Register Themselves': Astrophotography at the Early Lick Observatory," *The British Journal for the History of Science* 30, no. 2 (1997): 177–202; Pang, "Visual Representation and Post-constructivist History of Science," *Historical Studies in the Physical and Biological Sciences* 28 (1997): 139–171; Pang, "Technology, Aesthetics, and the Development of Astrophotography at the Lick Observatory," in *Inscribing Science: Scientific Texts and the Materiality of Communication*, ed. Timothy Lenoir (Stanford, CA: Stanford University Press, 1998), 223–248; Chaokang Tai "Left Radicalism and the Milky Way: Connecting the Scientific and Socialist Virtues of Anton Pannekoek," *Historical Studies in the Natural Sciences* 47, no. 2 (2017): 200–254; Janet Vertesi, *Seeing Like a Rover: How Robots, Teams, and Images Craft Knowledge of Mars* (Chicago: University of Chicago Press, 2015) and references cited therein.

7. See for example Michael Lynch and Samuel Y. Edgerton Jr., "Aesthetics and Digital Image Processing: Representational Craft in Contemporary Astronomy," *The Sociological Review* 35 (1987): 184–220; Michael Lynch and Samuel Y. Edgerton Jr., "Abstract Painting and Image Processing," in *The Elusive Synthesis: Aesthetics and Science*, ed. Alfred I. Tauber, vol. 182 (Boston: Kluwer Academic Publishers, 1996), 103–124; Messeri, *Placing Outer Space* (n.6); Vertesi, *Seeing Like a Rover* (n.6). An example of an exception to this is Charlotte Bigg, "Travelling Scientist, Circulating Images and the Making of the Modern Scientific Journal: Norman Lockyer's Visual Communication of Astrophysics in Nature," *Nuncius* 30, no. 3 (2015): 675–698.

8. We thank Erik Curiel for his valuable thoughts on the word "illusion" in relation to black hole imaging.

the spacetime in the vicinity of the black hole."[9] He noted that due to the strong curvature, it would in fact be possible for an observer to see light *behind* the black hole from their point of view. In the history of art, such seemingly impossible perspectives were typically presented as visual illusions to confound the beholder, showing them different parts of an image that did not fit together, and making them aware of their perception. We argue that Luminet did emphasize "optical distortions" in his drawing but did so to further intuition about black holes rather than to confound.

At the same time, Luminet described his drawing as "realistic." One of his intentions with the drawing was to promote belief in the existence of black holes among astronomers. In addition to the question of existence, Luminet used "realistic" to emphasize that his image took into account physical effects that would influence how the surroundings of the black hole looked to an observer. He also tied "realistic" to photography, describing his image as a "simulated photograph," and the observer as a photographic plate. Luminet textually framed his drawing as a photograph. He depicted his "simulated photograph" in a naturalistic style using *stippling* (drawing or painting with little dots) and a perspective technique called *chiaroscuro*.[10] We understand naturalism as a style in the visual arts (sometimes used interchangeably with realism, although this is contested) as the aim to depict objects in detail as they appear to the eye, using visual techniques such as perspective.[11] In painting and drawing, *chiaroscuro* is the use of contrasts between light and darkness to give the illusion of spatial depth on a flat surface. This was important for revealing curved space and depicting the "realistic physical properties" Luminet wanted to show.[12]

In the final section, we follow the ways aiming for "realistic" black hole imaging, and emphasizing apparent distortions arising in the space around a black hole, were reflected in the reception of Luminet's image. The drawing was discussed when new important black hole images were produced. The

9. Luminet, *Black Holes* (n.3), 143; Luminet, "40 Years of Black Hole Imaging (1) (n.4).

10. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 228.

11. For naturalism and related concepts, see David Summers, *The Judgment of Sense: Renaissance Naturalism and the Rise of Aesthetics* (Cambridge: Cambridge University Press, 1990), 3–9; on naturalism, Martin Kemp, "Taking it on Trust: Form and Meaning in Naturalistic Representation," *Archives of Natural History* 17, no. 2 (1990): 127–188; and on perspective and naturalism, James Elkins, *The Poetics of Perspective* (Ithaca, NY: Cornell University Press, 1994), 11. See also Erwin Panofsky, "Perspective as Symbolic Form," trans. Christopher S. Wood (New York: Zone Books, 1991 [1927]).

12. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 231.

science fiction film *Interstellar* (2014) was promoted for providing the first accurate black hole representation in a Hollywood film.[13] Yet it was not entirely accurate, deliberately avoiding some of the effects visible in Luminet's drawing, and later simulations. An image according to what astrophysicists such as Luminet believed was "realistic" was deemed too strange even for the genre of science fiction: certain visual effects were neglected to help the beholder make some sense of what they were looking at. With the release of the image shown in figure 1, early black hole imaging by Luminet and others was not just treated in terms of how realistic they were but also viewed in terms of how they had predicted features of the image shown in figure 1. Peer-reviewed papers focusing on images based on calculations and simulations (by Luminet and others) were cited in five of the first six publications released in connection with the image shown in figure 1, and they were presented as predictions of visual aspects of imaging from observation.[14] For example, Luminet was cited for having first suggested with his simulation "a bright ring or crescent shape."[15] This suggests that images based on simulations are sometimes considered scientific predictions in their own right in astrophysics.

BEHIND A BLACK HOLE

"In order to be visible," Luminet wrote in his *Astronomy & Astrophysics* paper, "a black hole has of course to be illuminated."[16] The year before, Luminet had carefully constructed a drawing of the light close to a black hole while working

13. James et al., "Gravitational Lensing by Spinning Black Holes in Astrophysics, and in the Movie *Interstellar*" (n.2). Luminet's 1979 paper was also cited in Kip Thorne, *The Science of Interstellar* (New York: W. W. Norton & Company, 2014).

14. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 1. The Shadow of the Supermassive Black Hole," *The Astrophysical Journal Letters* 875, no. 1 (2019): L1; Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 2. Array and Instrumentation," *The Astrophysical Journal Letters* 875, no. 1 (2019): L2; Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 4. Imaging the Central Supermassive Black Hole," *The Astrophysical Journal Letters* 875, no. 1 (2019): L4; Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 5. Physical Origin of the Asymmetric Ring," *The Astrophysical Journal Letters* 875, no. 1 (2019): L5; Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 6. The Shadow and Mass of the Central Black Hole," *The Astrophysical Journal Letters* 875, no. 1 (2019): L6.

15. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 2" (n.14), 2.

16. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 228.

at the Paris-Meudon Observatory. The drawing was made at the time that numerical simulations were done by "punched cards, and no visualization device was available, so that I had to produce the final image by hand from numerical data."[17] After performing a series of calculations by hand and writing the computer program on punched cards on an IBM 7040 computer, Luminet obtained rough illustrations from a drawing device available with the machine and then began the stages of his drawing.[18] First drawing a grid to correctly place the dots on a large transparent Canson paper, Luminet marked light points surrounding the black hole based on the computer simulation he had run. Bringing this stippling drawing in the negative (where the light appeared black and the region with the black hole looked white) to a photographic laboratory, Luminet inverted the image such that its center contained a dark orb, surrounded by light from the accretion disk of the black hole.[19]

Luminet's drawing (figure 2) was first released in November 1978 in the article "Les Trous Noirs: Maelströms Cosmiques," published in the French popular science magazine *La Recherche*.[20] According to Luminet, Australian theoretical physicist Brandon Carter, advisor on the PhD Luminet had earned in 1977, had encouraged him to produce a visualization. By early 1978, Luminet's work had centered on mathematical physics, and Carter knew of his interest in black holes. He also knew of Luminet's drawing skills because Luminet had shown him some of his M. C. Escher–inspired drawings. A visualization of a black hole, Carter suggested, could increase Luminet's chances for a position in astrophysics at Paris-Meudon Observatory at the Centre National de la Recherche Scientifique. Luminet began the calculations in the spring of 1978 and submitted the article to *Astronomy & Astrophysics* in July; it was published the year after. While the article was undergoing peer

17. Jean-Pierre Luminet, "From Black Holes to Cosmology: The Universe in the Computer," *Journal of Physics: Conference Series* 523, no. 1 (2014), 5.

18. Jean-Pierre Luminet, e-mail correspondence with the first author, 31 Aug 2018. On materiality and computer practices in scholarship, see Edgar Lejeune, *Médiévistes et Ordinateurs: Organisations Collectives, Pratiques des Sources et Conséquences Historiographiques (1966–1990)* (PhD dissertation, Université de Paris/Université Paris Diderot) and references cited therein.

19. Luminet, e-mail correspondence with first author, 2 Nov 2016.

20. Brandon Carter and Jean-Pierre Luminet, "Les Trous Noirs: Maelströms Cosmiques," *La Recherche* 9, no. 94 (1978): 944–953. The authors were aware of earlier black hole depictions. In their article, Carter and Luminet cited the book in which Bardeen's paper ("Timelike and Null Geodesics in the Kerr Metric," n.2) was published. Luminet cited Cunningham and Bardeen's paper "The Optical Appearance of a Star Orbiting an Extreme Kerr Black Hole," in "Image of a Spherical Black Hole with Thin Accretion Disk" (both in n.2).

review, Carter was preparing an introduction to black holes in *La Recherche*, targeting a French-speaking lay audience. Carter asked Luminet to help him co-author the article since Carter "was not familiar with popularization."[21]

Despite brief references to telescopic observation, Luminet's drawing came decades before observing a black hole shadow was seriously considered as something that could be done (although Luminet did indicate that the black hole candidate in the galaxy M87 could potentially be similar to his image). His drawing was not made on the basis of how it would look with a telescopic observation from Earth. Rather, Luminet used the notion of an "observer" as it appears in General Relativity (GR). In the context of GR, the term "observer" really represents, as historian of science Daniel Kennefick has phrased it, a "point of view . . . embodied in the geometrical coordinates chosen for the calculation."[22] Yet Einstein's thought experiments of "hurtling trains, spinning

21. Luminet, e-mail correspondence with the first author, 31 Aug 2018.

22. Daniel Kennefick, *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves* (Berlin & Princeton, NJ: Princeton University Press, 2016), 47. For the vast body of literature on the history of General Relativity, we refer to sources cited in Alexander Blum, Roberto Lalli, and Jürgen Renn, "The Reinvention of General Relativity: A Historiographical Framework for Assessing One Hundred Years of Curved Space-time," *Isis* 106, no. 3 (2015): 598–620; Blum, Lalli, and Renn, eds., *The Renaissance of General Relativity in Context* (Switzerland: Springer, 2020); Luís C. B. Crispino and Daniel J. Kennefick "A Hundred Years of the First Experimental Test of General Relativity," *Nature Physics* 15: 416–419; John Earman, Michel Janssen, and John D. Norton, *The Attraction of Gravitation: New Studies in the History of General Relativity* (Boston: Birkhäuser, 1993); David Kaiser, "A ψ is just a ψ? Pedagogy, Practice, and the Reconstitution of General Relativity, 1942–1975," *Studies in History and Philosophy of Modern Physics* 29 (1998): 321–338; Kaiser, "Whose Mass is it Anyway? Particle Cosmology and the Objects of Theory," *Social Studies of Science* 36 (2006): 533–564; and Kaiser, "Foreword to the 2017 edition," in Charles Misner, Kip Thorne, and John Wheeler, *Gravitation* (Princeton, NJ: Princeton University Press, 2017), xxlii–xxxi; Roberto Lalli, *Building the General Relativity and Gravitation Community during the Cold War* (Switzerland: Springer, 2017); Roberto Lalli, Riaz Howey, and Dirk Wintergrün, "The Dynamics of Collaboration Networks and the History of General Relativity, 1925–1970," *Scientometrics* 122, no. 2 (2020): 1129–1170; Dennis Lehmkuhl, "General Relativity as a Hybrid Theory: The Genesis of Einstein's Work on the Problem of Motion," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 67 (2019): 176–190; Richard Staley, *Einstein's Generation: The Origins of the Relativity Revolution* (Chicago: University of Chicago Press, 2008); and Jeroen van Dongen, *Einstein's Unification* (Cambridge: Cambridge University Press, 2010). For secondary accounts of the history of black hole research and their precursor, see Erik Curiel, "The Many Definitions of a Black Hole," *Nature Astronomy* 3, no. 1 (2019): 27–34; Jean Eisenstaedt, "Dark Bodies and Black Holes, Magic Circles and Montgolfiers: Light and Gravitation from Newton to Einstein," *Science in Context* 6, no. 1 (1993): 83–106; Eisenstaedt, *The Curious History of Relativity* (n.2); Stefano Furlan, "John Wheeler Between Cold Matter and Frozen Stars: The Road towards Black Holes" (Berlin: Max-Planck-Institut für Wissenschaftsgeschichte, 2021), http://hdl.handle.net/21.11116/

disks, and accelerating elevator" were rich with imagery, specifically to aid in communicating his accounts to non-specialists.[23] In these vivid images, the observer could be described as a human being, for instance using a clock and rigid rods for measurements. This textual imagery of the observer as a human being continued in peer-reviewed literature and textbooks on GR and black holes. In Robert Oppenheimer and Hartland Snyder's famous 1939 paper, for example, we find that the local observer can "see matter falling inward with a velocity very close to that of light."[24] With the emergence of black hole imaging, the observer came to be framed as a point of view in a visual sense: the "observer" was now imagined to be equipped with a camera or was described as a photographic plate.[25] Indeed, in some instances, the observer was referred to as "the photographer."[26]

In order to produce the visualization of how a black hole would appear if observed, Luminet first calculated the geodesics of light in the gravitational field of a black hole. Geodesics in this context means straight lines in curved space, and in this case, they represented light trajectories close to the black hole. To illustrate this in his *Astronomy & Astrophysics* paper, Luminet began with a thought experiment in which a parallel beam of light was projected from a distant source toward a "bare black hole" (words used here to describe a black hole without an accretion disk).[27] This was visualized by means of a human hand pointing a flashlight toward a black circle on a gray background (figure 3). This visualization of a thought experiment perhaps resembles visual

0000-0007-E8B9-3 (accessed 5 Sep 2022); Colin Montgomery, Wayne Orchiston, and Ian Whittingham, "Michell, Laplace and the Origin of the Black Hole Concept," *Journal of Astronomical History and Heritage* 12 (2009): 90–96; Carla Rodrigues Almeida, "Stellar Equilibrium vs. Gravitational Collapse," *The European Physical Journal H* 45, no. 1 (2020): 25–48; Simon Schaffer, "John Michell and Black Holes," *Journal for the History of Astronomy*, 10 (1979): 42–43.

23. Peter Galison, "The Suppressed Drawing: Paul Dirac's Hidden Geometry," *Representations* 72 (2000): 145–166, on 146. See also Peter Galison, *Einstein's Clocks and Poincaré's Maps: Empires of Time* (London: Sceptre, 2003).

24. Robert Oppenheimer and Hartland Snyder, "On Continued Gravitational Contraction," *Physical Review* 56 (1939): 455–459, on 456.

25. The latter was the case with Luminet's 1979 paper ("Image of a Spherical Black Hole with Thin Accretion Disk" [n.2], 228, 230, 232, 234).

26. See especially Jun Fukue and Takushi Yokoyama, "Color Photographs of an Accretion Disk Around a Black Hole," *Publications of the Astronomical Society of Japan* 40 (1988): 15–24. Changes to points of view in the history of black hole imaging have been presented in further detail in Skulberg, "The Event Horizon as a Vanishing Point" (n.1).

27. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 228.

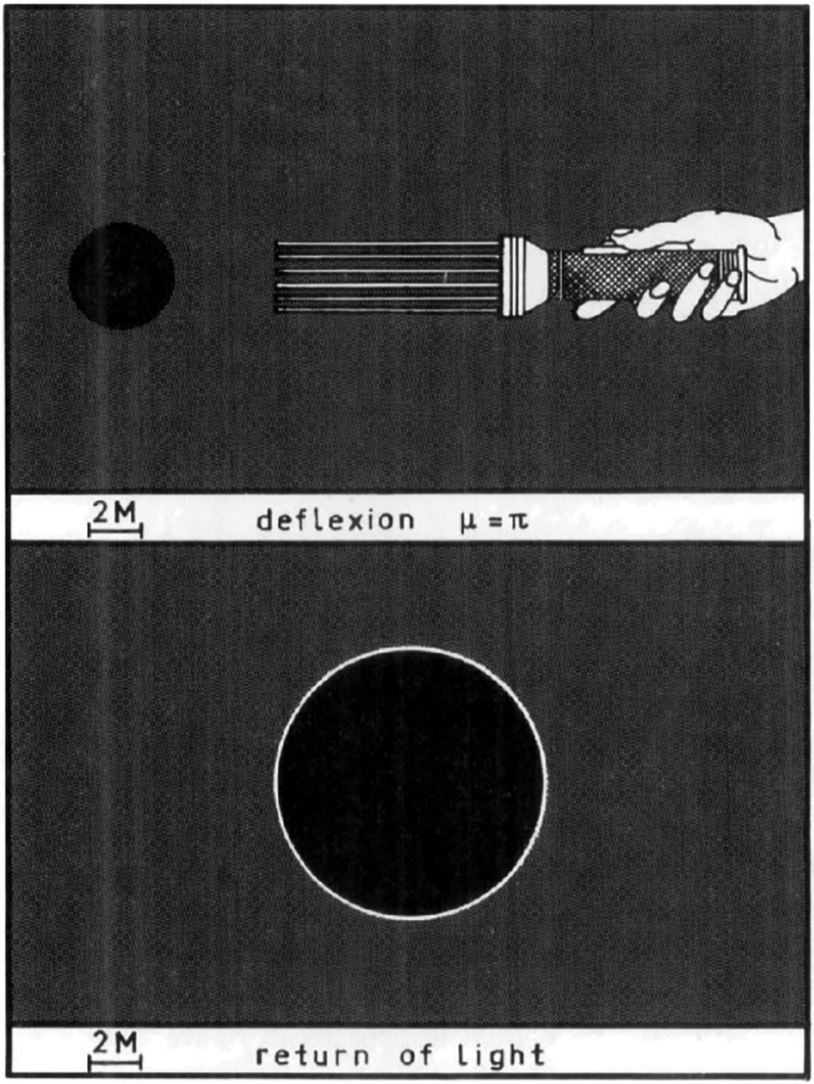

FIGURE 3. "Return of light deflected by 180 degrees from a bare black hole." From Jean-Pierre Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk," *Astronomy & Astrophysics* 75 (1979). Courtesy of Jean-Pierre Luminet.

conventions from physics and chemistry textbooks, particularly the depiction of hands in illustrations of experiments (for instance in textbooks such as Atkinson's translation of Ganot's *Éléments de Physique* and Gregory and Simmon's *Elementary Physics and Chemistry: Second Stage*), but it should be

noted that Luminet does not recall inspiration from such sources.[28] The visualized thought experiment showed that the image that reached the observer (at least what could be resolved) looked like a halo surrounding the black hole. Proceeding from this thought experiment, Luminet analyzed a "Clothed Black Hole" (in reference to a black hole with an accretion disk).[29] Similar to the beam of light, illustrated by the flashlight in figure 3, the radiation from the accretion disk was what revealed the presence of the black hole.

Luminet not only visualized the surroundings of a black hole but also schematically depicted the relationship between the observer and the black hole.[30] In the diagram shown in figure 4, Luminet placed the black hole on the left (the black circle). The position of the observer was specified as being 10 degrees above the plane of the accretion disk, as shown by the dashed line. The accretion disk was marked by the horizontal line. The lines around the black hole represented geodesics, which, as mentioned above, showed light trajectories. Four trajectories were examined by Luminet. Whereas trajectory 1 circled the black hole, trajectories 2 and 3 showed light behind and in front of the black hole (as seen from the observer's position). That is, the upper part of the accretion disk—both in front of the black hole and behind it—was visible due to the spacetime curvature. It did not stop there: trajectory 4 showed light from the lower part of the accretion disk.

In a later account of black hole imaging, Luminet communicated what he had depicted in 1978 as "[o]ptical distortions," "extraordinary optical deformations, due to the deflection of light rays;" the image was "considerably distorted."[31] Because of these "distortions," "we can see the top of the disk in its totality, whatever the angle from which we view it

28. R. A. Gregory and A. T. Simmons, *Elementary Physics and Chemistry: Second Stage* (London: MacMillan, 1900); and A. Ganot and E. Atkinson, *Elementary Treatise on Physics Experimental and Applied*, 10th edition (London: Longmans, Green, and co., 1881).

29. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 230.

30. Representations of the relations between points of view are far from new. In Elkins's account of *perspective schemas*, he noted how such illustrations were often included at the beginning of manuals, monographs, and essays on perspective to show linear perspective by tracing geometrical lines on a wall or a pane of glass in front of an observer (Elkins, *The Poetics of Perspective* [n.11], 9). Illustrations were used to depict the observer from a point of view outside them in order to explain spatial relations in connection with the way space looks from a given point of view, and how it should be depicted. Another comparison is the earlier history of optics, e.g. the *Magia Naturalis* by Giovanni Battista della Porta where optical artefacts were seen as illusions as well as useful for natural philosophy. On this, see Olivier Darrigol, *A History of Optics from Greek Antiquity to the Nineteenth Century* (Oxford: Oxford University Press, 2012).

31. Luminet, "40 Years of Black Hole Imaging (1)" (n.4).

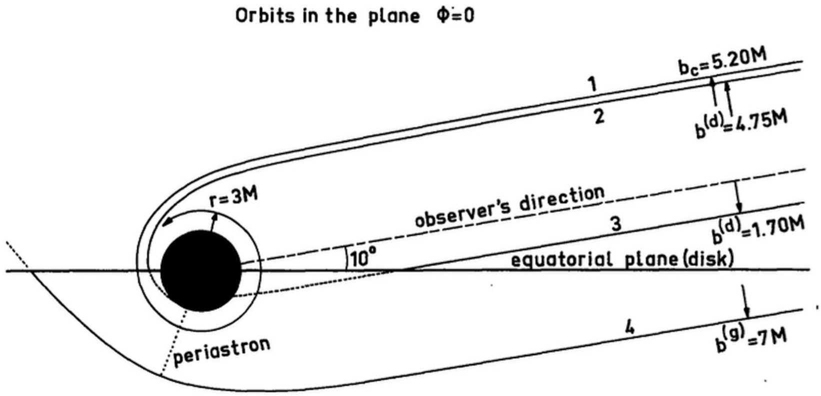

FIGURE 4. "Illustrative orbits in the plane." From Jean-Pierre Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk," *Astronomy & Astrophysics* 75 (1979). Courtesy of Jean-Pierre Luminet.

may be."[32] He also emphasized the "apparent" position of the light and the "apparent diameter of the hole."[33] Formulations like this were common in the early history of black hole imaging. In 1973, two semi-schematic illustrations were described as depicting the "apparent position" of a star close to the black hole, as well as the "apparent angular size," "apparent luminosity," and the "apparent shape of the black hole."[34] Black hole researchers stressed the difference between the "actual" location of light and its "apparent" position as seen by an observer. What is interesting about Luminet's approach is how he focused on "optical distortions" to make black holes intuitive to audiences.[35] What we mean by intuition—in this context—is a sense of the space around a black hole through the use of perspective. This intuition was used to promote scientific understanding of black holes (here in the sense of explaining the nature of what was not visible by visualizing the region around the black hole) and belief in their existence.[36] This is particularly relevant given the

32. Luminet, "40 Years of Black Hole Imaging (1)" (n.4). The disk in reference is the accretion disk.

33. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 229.

34. Cunningham and Bardeen, "The Optical Appearance of a Star Orbiting an Extreme Kerr Black Hole" (n.2), 237; Bardeen, "Timelike and Null Geodesics in the Kerr Metric" (n.2), 237, 232.

35. Luminet, "40 Years of Black Hole Imaging (1)" (n.4).

36. On scientific understanding, see Henk de Regt, *Understanding Scientific Understanding* (Oxford: Oxford University Press, 2017).

existing discussion surrounding visual representations in GR and intuition. Art historian Martin Kemp argued that curved spaces as described in GR

> remain remote from general public understanding and resistant to visualization and representation in terms of our normal and ingrained experience of the phenomenological world. They are intellectual constructs that we have been unable to naturalize in our automatic responses to spatial experience and representation.[37]

In his study of Penrose diagrams, historian and philosopher Aaron Sidney Wright opposed Kemp's view, and showed that these diagrams were "drawn in perspective and shaded 'realistically.'"[38] By doing so, Penrose shaped the complex mathematics of GR into *paper tools*, which were helpful for researchers as well as students in gaining intuition.[39] Our study of Luminet's use of his drawing (figure 2) supports Wright's argument that images used in the context of GR research and pedagogy can play important roles in furthering intuition. Luminet used his drawing not just in communication with specialists but in popular books and articles, blog posts, and presentations. As we will see, explaining the perspective his image was based on was part of how he communicated black holes.

Perspective, as art historian Ernst Gombrich wrote,

> rests on a simple and incontrovertible fact of experience, the fact that we cannot look round a corner. It is due to this unfortunate inability of ours

37. Martin Kemp, *Seen/Unseen: Art, Science, and Intuition from Leonardo to the Hubble Telescope* (New York: Oxford University Press, 2006), 82.

38. Aaron Sidney Wright, "The Origins of Penrose Diagrams in Physics, Art, and the Psychology of Perception, 1958–62," *Endeavour* (New series) 37, no. 3 (2013): 133–139, on 136. See also Aaron Sidney Wright, "The Advantages of Bringing Infinity to a Finite Place: Penrose Diagrams as Objects of Intuition," *Historical Studies in the Natural Sciences* 44, no. 2 (2012): 99–139.

39. See Ursula Klein, *Experiments, Models, Paper Tools: Cultures of Organic Chemistry in the Nineteenth Century* (Stanford, CA: Stanford University Press, 2003); and Kaiser, *Drawing Theories Apart* (n.6) for diagrams viewed as *paper tools*. See also Hentschel's comments on the diagrams in Charles W. Misner, Kip S. Thorne, and John A. Wheeler's *Gravitation* (New York: W. H. Freeman, 1973) in Hentschel, *Visual Cultures in Science and Technology* (n.6); Stefano Furlan, "Down the Maelström: John A. Wheeler between Cosmic Imagery and the Roots of Quantum Gravity" (in prep.); and Furlan, "John Wheeler between Cold Matter and Frozen Stars: The Road towards Black Holes" (n.21) for studies of diagrams as part of Wheeler's work. On Wheeler, see also Alexander Blum and Stefano Furlan, "How John Wheeler Lost his Faith in the Law," in *Rethinking the Concept of Law of Nature: Natural Order in the Light of Contemporary Science*, ed. Yemima Ben-Menahem (Cham: Springer, 2022), 283–322 and sources cited therein.

that as long as we look with one stationary eye, we see objects only from one side and have to guess, or imagine, what lies behind.[40]

Yet Luminet showed that this is not the case when it comes to the space around a black hole. His "simulated photograph" (i.e., drawing) showed the light from *behind* the black hole from the point of view of the observer. Gravitational lensing is, of course, not limited to the space around black holes. The study of lensing effects has been essential in the history of GR. It played a central role in the making and interpretation of the photographs and other visual representations tied to the 1919 solar eclipse observations.[41] What is important about Luminet's framing is that he used the apparent impossibility of what the image showed (seeing matter behind the black hole) to promote intuition about an object posing a significant challenge to the beholder's intuitions.

Returning to Gombrich, the art historian explored several examples of perspectives that did not seem to make sense. One way to image spatial relations in the visual arts is by "overlapping"—to place something closer to an observer in front of something further away. A joke was played on this and other perspective techniques in Hogarth's frontispiece providing a satire on "false perspective" (figure 5). Hogarth used (deliberately wrong) perspective techniques, creating an "impossible world."[42] For example, the trees appeared to be in front of the sign, rather than the other way around. Whereas Hogarth played with confusing the beholder, Luminet used his diagram (figure 4) to introduce intuitions about curved spacetimes. He showed that in the case of the space around a black hole, it is indeed possible to see something behind it.

Another "impossible world" explored by Gombrich is found in the work of M. C. Escher, which differs from Hogarth's work, Gombrich argued, by

40. Ernst H. Gombrich, *Art and Illusion: A Study in the Psychology of Pictorial Representation* (Oxford: Phaidon Press, 1960), 211. With many thanks to Stefano Furlan, it is also interesting that John Wheeler was in contact with Gombrich in 1979 and quoted *Art and Illusion.* See John Wheeler, "Law Without Law," in *Structure in Science and Art*, ed. Peter Medawar and Julian Shelley (Amsterdam: Excerpta Medica, 1980), 132–168, on 149.

41. On eclipse observations, see Jeffrey Crelinsten, *Einstein's Jury* (Princeton, NJ: Princeton University Press, 2013); Daniel Kennefick and Jeffrey Crelinsten, "Early Solar Eclipse Images and Tests of Relativity," *Physics Today* 73, no. 12 (2020): 10–11; Daniel Kennefick, *No Shadow of a Doubt: The 1919 Eclipse that Confirmed Einstein's Theory of Relativity* (Princeton, NJ: Princeton University Press, 2021); Matthew Stanley, *Practical Mystic: Religion, Science, and A. S. Eddington* (Chicago: University of Chicago Press, 2007); Matthew Stanley, *Einstein's War: How Relativity Triumphed amid the Vicious Nationalism of World War I* (New York: Dutton, 2019) and references cited therein.

42. Gombrich, *Art and Illusion* (n.40), 206.

FIGURE 5. Luke Sullivan (engraver) after William Hogarth, *Satire on False Perspective: Frontispiece to "Kirby's Perspective*," etching and engraving, 1754, 20.6 x 17.3 cm. The Metropolitan Museum of Art, New York.

making the perspective look correct rather than false.[43] And yet the illusions of spatial depth here present the beholder to "realms where terms such as 'up' and 'down' and 'right' and 'left' have lost their meaning."[44] This was not the case with Luminet's image: Luminet carefully explained the position of the

43. Gombrich, *Art and Illusion* (n.40), 206.
44. Gombrich, *Art and Illusion* (n.40), 207.

observer, the black hole, and the light trajectories to further the beholder's understanding. What would seem to be impossible was presented as real in his depiction (and as shown in the next section, Luminet emphasized that his image was "realistic").

Luminet was in fact inspired not only by the work of Escher but also Piranesi, two artists discussed in Gombrich's analysis of impossible perspectives. There is a direct link between Luminet's inspiration from Escher and the creation of his drawing (figure 2). Before delving into this, it is relevant to note that Luminet was not the only black hole researcher inspired by Escher. Among his many contributions to black hole research, Nobel Laureate Sir Roger Penrose has introduced a variety of schematic representations to the field of GR. Besides building upon the visual tradition of spacetime diagrams, Penrose had engaged with a visual tradition rooted in art and psychology, which was also important to the schematics he created.[45] Together with his father Lionel (who amongst others had a background in psychology), Penrose produced two articles in 1958, showcasing "impossible objects."[46] In their contribution to the *British Journal of Psychology*, they cited a catalogue for an exhibition by Escher and elaborated their thoughts on "impossible objects" such as the triangle with conflicting perspectives (now known as the "Penrose triangle"), writing, "As the eye pursues the lines of the figure, sudden changes in the interpretation of distance of the object from the observer are necessary."[47] In his novel relativistic diagrams, Penrose used conformal transformations (these preserve angles while distorting scale) in a way that enabled him to represent infinity in finite points and lines in his diagrams.[48]

45. Wright, "The Advantages of Bringing Infinity to a Finite Place"; Wright, "The Origins of Penrose Diagrams in Physics, Art, and the Psychology of Perception, 1958–62" (both in n.38).

46. Lionel S. Penrose and Roger Penrose, "Impossible Objects: A Special Type of Visual Illusion," *British Journal of Psychology* 49, no. 1 (1958): 31–33; Penrose and Penrose, "Puzzles for Christmas," *New Scientist* (Dec) 1958, 1580–1581. Escher was also inspired by Penrose's work, and the two exchanged letters. See Gustaaf C. Cornelis, "Analogical Reasoning in Modern Cosmological Thinking," in *Metaphor and Analogy in the Sciences*, ed. Fernand Hallyn (Dordrecht: Kluwer Academic Publishers, 2000), 165–180. On optical illusions and astronomy, see Chaokang Tai, "The Milky Way as Optical Phenomenon," in *Anton Pannekoek: Ways of Viewing Science and Society,* ed. Chaokang Tai, Bart van der Steen, and Jeroen van Dongen (Amsterdam: Amsterdam University Press, 2019), 219–247.

47. Penrose and Penrose, "Impossible Objects" (n.47), 31.

48. Roger Penrose, "The Light Cone at Infinity," in *Relativistic Theories of Gravitation: Proceedings of a conference held in Warsaw and Jabłonna July, 1962,* ed. Leopold Infeld (Oxford: Pergamon Press, 1964), 369–373.

Luminet's engagement with drawing and inspiration from Escher was present long before the production of his drawing. According to his recollections, Luminet first became aware of Escher's work at the age of sixteen. The first version of one of Luminet's artistic lithographies, *L'Observatoire (Hommage à Escher),* was made in the late 1960s using black Indian ink; this drawing was directly inspired by Escher.[49] When Luminet produced his drawing a decade later, he again used Indian ink and challenged the beholder's intuition, as Escher had done. His interest in Escher continued after the publication of his drawing. The cover of his book *Black Holes*, published in 1992, showed one of Luminet's Escher-inspired artworks.[50] Both Penrose and Luminet were inspired by Escher, and we can link their inspiration to the creation of visual representations. But the images they created were used in different ways. Luminet did not create a paper tool in the form of a diagram used to make calculations. Schematics were included in Luminet's publications only to aid beholders in the interpretation of his drawing (figure 2). Unlike the use of Penrose diagrams in advanced pedagogy and research, Luminet targeted audiences who were familiar with GR, as well as audiences who were not. Wright noted that Penrose used perspective techniques, particularly shading, to give a sense of grappling with an object when doing calculations.[51] In the naturalistic style of Luminet's drawing, the use of shading was closer to chiaroscuro (carefully portraying differences between light and darkness in the image to give a sense of spatial depth).[52] While "optical distortions" appearing around a black hole might challenge the intuition of the beholder, Luminet explained to the reader what they were looking at, and he has continued

49. Luminet, e-mail correspondence with first author, 31 Aug 2018. Some of Luminet's lithographies can be seen here: Jean-Pierre Luminet, "Encres, lithographies et collages de J.-P. Luminet," https://luth2.obspm.fr/~luminet/Art/lithos.html (accessed 6 Sep 2022).

50. Luminet, *Black Holes* (n.3). On Luminet's art, see Martin Kemp, "Luminet's Illuminations: Cosmological Modelling and the Art of Intuition," *Nature* 426 (2003): 232.

51. Wright, "The Advantages of Bringing Infinity to a Finite Place" and "The Origins of Penrose Diagrams in Physics, Art, and the Psychology of Perception, 1958–62" (both in n.38). Stefano Furlan has noted that the same was the case with Wheeler's diagrams (conversation with first author, 24 Nov 2020).

52. Similarly, scholars such as art historian Samuel Y. Edgerton Jr. have argued that shading tied visuality and knowledge in interesting ways in the work of Galileo (*The Mirror, the Window, and the Telescope: How Renaissance Linear Perspective Changed Our Vision of the Universe* (Ithaca, NY: Cornell University Press, 2009). See also Horst Bredekamp, "Gazing Hands and Blind Spots: Galileo as Draftsman," *Science in Context* 13, no. 3–4 (2000): 423–462; and John L. Heilbron, *Galileo* (Oxford: Oxford University Press, 2012). Galison connected Galileo's washes of the Moon to the image shown in figure 1, see Galison, "Philosophy of the Shadow" (n.1).

to do so in books, articles, presentations, on social media, and his blog. "Optical distortions" were used not to confound beholders but to help further intuition about a highly unusual region of spacetime. We have also seen in this section how Luminet was inspired by Escher, whose work was interpreted by scholars such as Gombrich as otherworldly. But as we show in the following section, Luminet's "simulated photograph" was instead presented as "realistic."

A "REALISTIC" IMAGE

In 2019, Luminet was invited to give a keynote talk at the Black Hole Initiative Conference at Harvard University, which was held shortly after the release of the image shown in figure 1. Here, he expressed that one of his intentions with producing his drawing (figure 2) was simply that "I liked very much the idea to show—for the first time—the invisible in some way."[53] In addition, he wanted to make black holes seem more real to researchers who doubted their existence at the time.[54] There were disciplinary elements to this intention. As mentioned above, Luminet's background was in mathematical physics. Yet, after changing institutions, he experienced how "I was surrounded at the Paris Observatory mostly by classical astronomers who did not believe in the existence of an object they could not see."[55] Thus Luminet created his drawing to convince astronomers (accustomed to working in a highly visual field) of the existence of black holes. In fact, Luminet submitted his paper about his drawing (figure 2) to *Astronomy & Astrophysics*, indicating that astronomers were among his target audience.[56] Luminet's paper was published at a time when black holes were considered a curiosity by many researchers. An important moment for the exchange between astrophysics and GR in black hole research came with the first Texas Symposium on Relativistic Astrophysics in 1963, where research within GR and astrophysics converged on a large scale.[57] Among the chief

53. Luminet, "Black Hole Imaging" (n.4).

54. Ibid.

55. Ibid.

56. We are grateful to Omar Nasim, who noted that the visual culture of astronomy might have influenced the use of images to persuade this community of the existence of black holes.

57. Marcia Bartusiak, *Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled on by Hawking Became Loved* (New Haven, CT: Yale University Press, 2015), 123–125. See also Engelbert L. Schucking, "The First Texas Symposium on Relativistic Astrophysics," *Physics Today* 42, no. 8 (1989): 46–52.

topics discussed at the symposium were whether observed quasars could be caused by "superstars" (supermassive black holes). Some researchers found this convincing but not all: black holes remained up for debate in the 1970s and into the 1980s. Observations of Cygnus X-1 in the early 1970s were also discussed as potential evidence for the existence of black holes. In December 1974, only a few years before Luminet created his drawing (figure 2), Stephen Hawking and Kip Thorne made their famous bet on whether Cygnus X-1 was, in fact, a black hole. The idea of black holes in the universe remained an unsettled matter.

If one of Luminet's motivations for producing the image was to convince astronomers that black holes existed, there is a sense in which the use of his drawing could be seen in the light of scientific realism as it is discussed in the philosophy of science. While a multitude of competing definitions are used, a recent account of entity realism in astrophysics focusing on black holes is perhaps particularly relevant: "Scientific realism is a philosophical doctrine that seeks to carve out the specific conditions under which we may rationally believe that a scientific theory is true, or when its objects are real."[58] Although scientific realism and naturalism (or visual realism) in the visual arts discuss different subject matters, bodies of literature from various fields carry some common ground. As Kaiser has noted, discussions in science studies have explored the question of whether scientific images should be seen as constructions or "pictur[ing] the world as is."[59] Kaiser highlighted a similar discussion taking place in art history about whether realism in the arts is a particularly

58. Simon Allzén, "Extragalactic Reality Revisited: Astrophysics and Entity Realism," in *Philosophy of Astrophysics: Stars, Simulations, and the Struggle to Determine What is Out There*, ed. Nora Mills Boyd, Siska De Baerdemaeker, Kevin Heng, and Vera Matarese (Cham: Springer, 2023): 277–293, on 277. In the same volume, see also Juliusz Doboszewski and Dennis Lehmkuhl, "On the Epistemology of Observational Black Hole Astrophysics," 225–247. On realism, see Hasok Chang, *Realism for Realistic People: A New Pragmatist Philosophy of Science* (Cambridge: Cambridge University Press, 2022). In a similar vein, scientific realism and dark matter are explored in Niels C. M. Martens, "Dark Matter Realism," *Foundations of Physics* 52, no. 16 (2022): 1–19. On dark matter, see also Niels C. M. Martens, Miguel Ángel Carretero Sahuquillo, Erhard Scholz, Dennis Lehmkuhl, Michael Krämer "Integrating Dark Matter, Modified Gravity, and the Humanities," *Studies in History and Philosophy of Science* 91 (2022): A1–A5; Jaco de Swart, Gianfranco Bertone, and Jeroen van Dongen, "How Dark Matter Came to Matter," *Nature Astronomy*, 1 (2017), 0059; and Jaco de Swart, "Closing in on the Cosmos: Cosmology's Rebirth and the Rise of the Dark Matter Problem," in *The Renaissance of General Relativity in Context: Einstein Studies, vol. 16*, ed. Alexander S. Blum, Roberto Lalli, and Jürgen Renn (Cham: Birkhäuser, Springer, 2020), 257–284.

59. Kaiser, *Drawing Theories Apart* (n.6), 361.

"natural" kind of representation of phenomena or whether it is more appropriate to see realism as a learned habit or a convention.[60] As mentioned, in art history, realism is sometimes used interchangeably with naturalism, but it also has several other definitions. In art history, "realism" is not only used to describe the mid-nineteenth-century art movement or the lack of idealization but, more broadly, realism "is at base a category of subject matter, and refers to art having a concrete historical reference or an apparent concrete historical reference."[61] On this understanding, realism is not interchangeable with naturalism. Referring to works such as Hieronymus Bosch's depictions of real and imaginary animals, Kemp noted that the naturalistic style with which the animals were depicted would make a unicorn seem as real as a giraffe to the Renaissance spectator.[62] In other words, naturalistic depictions do not necessarily portray entities that are real, but the style can certainly be used with the aim of giving the sense that what is depicted has taken place or exists. In practice, the contextualization of scientific images can rarely be described neatly by one of the categories above. What is at play is often a mixture of naturalistic style (or imaging techniques perceived as more faithful, as has been addressed, for instance, in Daston and Galison's *Objectivity*) and claims of images representing natural phenomena as they are, or claims that such natural phenomena exist.[63] Take, for example, bubble chamber photographs and Feynman diagrams. The latter were seen by some physicists "as capturing *reality* more directly or completely than other visual tools did."[64] Physicist and historian David Kaiser argued that this understanding was in part based on the resemblance of the schematics to bubble chamber photographs.[65] This interesting overlap between the use of schematics and photographs was part of the reason the diagrams remained in use (although in

60. Gombrich, *Art and Illusion* (n.40); Nelson Goodman, *Languages of Art: An Approach to a Theory of Symbols* (Indianapolis: Hackett, 1976 [1968]). A more detailed account of this debate, and how it can be tied to scientific images, can be found in Kaiser, *Drawing Theories Apart* (n.6).

61. Summers, *The Judgment of Sense* (n.11), 3.

62. Kemp, "Taking it on Trust" (n.11), 128. See also Sachiko Kusukawa, *Picturing the Book of Nature: Image, Text, and Argument in Sixteenth-century Human Anatomy and Medical Botany* (Chicago: University of Chicago Press, 2012), 4–8, for a discussion on naturalism in the context of history of science.

63. Daston and Galison, *Objectivity* (n.6).

64. David Kaiser, "Stick-figure Realism: Conventions, Reification, and the Persistence of Feynman Diagrams, 1948–1964," *Representations* 70: 49–86, 51.

65. Ibid., 75.

quite different ways) for as long as they did.[66] Bubble chamber photographs, in turn, were described by historian and philosopher Peter Galison as images that were "presented, and defended, as *mimetic*—they purport to preserve the form of things as they occur in the world."[67] Kaiser and Galison both tied the existence of actual photographs to the claims made by physicists about visual representations depicting physical phenomena as they actually behave. What is interesting about Luminet's emphasis on photography and his drawing (figure 2) being "realistic" is that the shadow of a black hole had never been observed at the time. No photographs had been made. His drawing was an *imagined* photograph taken by an observer in space. Yet Luminet used this drawing to persuade beholders that black holes were real, and we will show how associations with photography were part of that, even decades before the release of the image shown in figure 1.

Such associations can be approached from many angles, as shown above, but our interest here is: how did Luminet present an image of an (at the time) unobservable object as "realistic"? We here use "realistic" as an actor's category. From our analysis of Luminet's varied uses of his drawing (figure 2) in several publications and presentations, we will show three aspects of how Luminet described the drawing as realistic: he made claims about the accuracy of his simulation based on physical effects taken into account, tied his drawing to photography, and implied the possibility of telescopic observation.

Luminet described his drawing as "realistic in the sense that it takes account of the physical properties of the gaseous disc."[68] The most central part of Luminet's understanding of his image being "realistic" was his taking into account "realistic physical properties," which would influence how the light near a black hole would appear to a distant observer.[69] Specifically, Luminet focused in his many communications of his drawing on the Doppler effect and the Einstein effect (now known as gravitational redshift). Luminet noted how the Doppler effect would make matter in the rotating disk moving toward the observer appear more luminous than matter moving away. The Einstein effect would lower the frequency and intensity of the signal because of the gravitational

66. Ibid., Kaiser, *Drawing Theories Apart* (n.6).
67. Galison, *Image and Logic* (n.6), 19.
68. Luminet, *Black Holes* (n.3), 144.
69. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 231.

field of the black hole.[70] As philosopher Laura Perini reminded us, it is useful to distinguish models from visual representations.[71] The *connection* between simulation and visualization here, though, is interesting: Luminet argued that his visual representation was accurate on the basis of the physical effects taken into account in his simulation. This was then used to argue that the image of something that had never been observed was an accurate representation.

We would also argue that Luminet's experience with the arts was crucial for showing the "realistic physical properties." Luminet himself does not recall inspiration from particular scientific visual conventions in astronomy but rather notes his interest in the arts when asked about stylistic choices. He did not take drawing lessons but experimented with techniques on his own. At roughly age eighteen, he recalls learning perspective techniques from a book and continuing to practice the techniques afterwards. He also mentioned how, at the time he created his drawing (figure 2), he was (like other relativists) fascinated by the figures included in *Gravitation*, the so-called bible of GR (but he did not indicate this influenced the creation of his drawing).[72] The styles of his drawing and figures in *Gravitation* differ, but geodesics also feature centrally in *Gravitation*. In his book *Black Holes*, Luminet likewise focused on visual conventions within the relativity community, such as space-time diagrams.[73] Thus we cannot claim a conscious use of particular visual conventions from astronomy, even if Luminet did hope to persuade astronomers that black holes could exist. Nonetheless, given the long history of drawing as a crucial part of practice in astronomy, it is not hard to imagine that Luminet's image could have appealed to astronomers. For example, we find in historian Omar Nasim's monograph on drawings of celestial nebulae in the nineteenth century how stippling, as well as Indian ink, was used.[74] There is therefore an overlap between Luminet's image and astronomical drawing not only with drawing

70. Luminet, "40 Years of Black Hole Imaging (1)" (n.4). See also Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), Luminet, "From Black Holes to Cosmology" (n.17), Luminet, "Black Hole Imaging" (n.4), Luminet, *Black Holes* (n.3).

71. Laura Perini, "Scientific Representation and the Semiotics of Pictures," in *New Waves in Philosophy of Science*, ed. P. D. Magnus and Jacob Busch (New York: Palgrave Macmillan, 2010), 148–151.

72. Luminet, e-mail correspondence with first author, 14 May 2023; Misner, Thorne, and Wheeler, *Gravitation* (n.39).

73. See particularly Luminet, *Black Holes* (n.3), chapter 12.

74. Nasim, *Observing by Hand* (n.6), 52. See also Simon Schaffer, "On Astronomical Drawing," in *Picturing Science, Producing Art*, ed. Peter Galison and Caroline A. Jones (New York: Routledge, 1998), 441–474.

technique but with materials. Some regions had more dots than others, making them appear brighter. Because of this, in Luminet's drawing, the Doppler and Einstein effects were visible through the asymmetric design of the image: the left-hand side of the disk looked brighter than the right-hand side. Luminet's drawing of the sharp contrast between light and darkness (*chiaroscuro*) enabled him to depict a region of spacetime with extreme curvature.

The question of negatives and positives also featured centrally in astronomical practice. In his paper "On Astronomical Drawing," published in 1846, Charles Piazzi Smyth noted how "Astronomical drawings may generally be divided into two large classes; the positive, or that in which shade is represented by blackness; and the negative, in which the lights are the darkest parts of the picture."[75] Smyth feared that negative drawings could cause confusion but "the simplest variety of the sensitive paper has rendered it so very easy to change a negative into a positive picture . . . under natural appearances."[76] In astronomy, observations are still frequently rendered in the negative. In his final drawing, however, Luminet chose to draw a negative, and then use a photographic laboratory to create a positive. One way of looking at the process of production of Luminet's drawing could be that he, similar to Smyth, wanted to represent the black hole "under natural appearances" (such that the black hole looked black). One could also point out that Luminet here seems to perform his own thought experiment: first, he positions the point of observation, by drawing a black hole as it would appear from ten degrees above the accretion disk. Then he, like his imagined observer, takes a photograph of this image and develops it in the photographic laboratory to obtain a positive.

"Realistic" was also used in the *Astronomy & Astrophysics* paper when referring to appearance and the (imagined) photography performed by the observer. The role photography did in fact play in Luminet's drawing (figure 2) was his use of the photographic laboratory. But that was not how he emphasized associations to photography in the descriptions of his drawing. As mentioned, in the *Astronomy & Astrophysics* paper, he presented his drawing as a "simulated photograph" and the observer as having a "photographic plate"

75. Quoted from the reprint of the paper "On Astronomical Drawing" (first published in *Memoirs of the Royal Astronomical Society* 15 [1846], 71–82), in Klaus Hentschel and Axel D. Whittmann. eds., *The Role of Visual Representations in Astronomy: History and Research Practice: Contributions to a Colloquium Held at Göttingen in 1999* (Frankfurt am Main: Deutsch, Thun, 2000), 67.

76. Ibid., 72.

for a detector.[77] This was not just a quirk of one paper, as Luminet continued using phrasings tied to photography as he discussed his drawing in the decades after its publication. The emphasis on the "photographic appearance" of a black hole and its accretion disk functioned as a more subtle characterization of the image as "realistic."[78]

But what was the purpose of the "realistic" image? Luminet did indeed include some references to telescopic observation, possibly in a bid to astronomers. In his *Astronomy & Astrophysics* paper, Luminet briefly discussed the relevance of the visualization from an "observational point of view."[79] By observation, Luminet referred to telescopic observation rather than a hypothetical "observer," perhaps implying that the surroundings of a black hole could in fact be observed. In *La Recherche*, Luminet's drawing was described as the "[r]ealistic photographic appearance of a spherical black hole surrounded by an accretion disk."[80] Here, "photographic appearance" and telescopic observation were tied together:

> In order to form a truly concrete image of a black hole, it is natural to try to imagine its visual appearance. In other words, can we imagine what a photograph of a black hole taken with a telescope located at a suitable distance from the black hole would look like?[81]

The question, Carter and Luminet wrote, could seem absurd "since we have already pointed out that a black hole is totally invisible by itself."[82] However, a black hole illuminated by a different source, such as a star or an accretion disk, is "perfectly observable."[83]

The image shown in figure 1—which was based on actual observation—is also sometimes described as a "photograph." After using multiple telescopes on Earth to observe the shadow of M87*, this image was created in numerous steps, from several data treatments to different imaging algorithms. Writing for

77. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 228.

78. Luminet, *Black Holes* (n.3), 145.

79. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 231.

80. Original: "Apparence photographique réelle d'un trou noir sphérique entouré d'un disque d'accrétion" Carter and Luminet, "Les Trous Noirs" (n.20), 945.

81. "Pour se former une image réellement concrète d'un trou noir, il est naturel de chercher à se représenter son apparence visuelle. En d'autres termes, peut-on imaginer ce que donnerait la photographie d'un trou noir qui serait prise au moyen d'un télescope situé à une distance convenable du trou noir?" Carter and Luminet, "Les Trous Noirs" (n.20), 948.

82. "Puisque nous avons déjà souligné qu'un trou noir est totalement invisible par lui-même" Carter and Luminet, "Les Trous Noirs" (n.20), 948.

83. "Parfaitement observables" Carter and Luminet, "Les Trous Noirs" (n.20), 948.

MoMA Magazine, Galison explored the multifaceted discussion of what a photograph is through an account of what the image (shown in figure 1) represents, and how it was created. Galison argued that, due to the fluid understanding of photography, the image might in fact be interpreted as a photograph. We have shown in this section how describing black hole images as "photographs" goes back decades before a black hole shadow was observed. We have also seen how associations with photography were part of how Luminet presented his image as "realistic." His drawing (figure 2) was an imagined photograph on the basis of a thought experiment. Luminet primarily used "realistic" to describe his taking into account physical effects that would influence how the accretion disk would appear to a distant observer, and these effects were depicted with his careful use of chiaroscuro. In addition to describing his drawing as "realistic" in the many contexts in which he used the image, Luminet expressed that he created the image to make black holes seem real to astronomers.

So far, we have shown how Luminet's paper used apparent "optical distortions" to convey the nature of what could not be seen, and how the image was at the same time presented as "realistic." These elements also came to form part of the reception of the image, as we will show in the following section. Whereas Luminet employed "optical distortions" to communicate the nature of black holes, a later science fiction film actually chose to *decrease* perceived realism by removing some of the physical effects. Even in the genre of science fiction, the space around a black hole was deemed too strange for beholders if all the physical effects were taken into account. At the same time, many continued to frame black hole imaging similarly to Luminet. For example, *Nature* reporter Davide Castelvecchi commented in a blog post that "the rise of powerful computers in the decades after Luminet's efforts meant researchers made ever more realistic simulations."[84] Not only was "realistic" used to present black hole imaging following Luminet's image, but his drawing and other early black hole representations, came to be treated as visual predictions of the image shown in figure 1.

VISUAL PREDICTIONS

For almost a decade, Luminet's image was *not* influential in shaping how black holes were viewed. The first citation of Luminet's 1979 article was by authors

84. Davide Castelvecchi, "Imaging and Imagining Black Holes," *A View over the Bridge:* Nature's *Books and Arts Blog* (28 Mar 2017): https://blogs.nature.com/aviewfromthebridge/2017/03/28/imaging-black-holes (accessed 23 Sep 2022).

who were part of Luminet's workplace, at the Observatoire de Meudon. One was Luminet's supervisor, Carter, who used Luminet's drawing to communicate research on black holes in a 1979 conference proceeding contribution, and then in 1981, another citation came from a paper by researchers at the Observatoire. These authors chose to include spectra and plots to help astronomers interpret observations of emission from accretion disks, rather than trying their hand at the naturalistic style Luminet had used.[85] Luminet's paper was cited in Subrahmanyan Chandrasekhar's *The Mathematical Theory of Black Holes*.[86] In 1985, Luminet's drawing appeared in a book chapter co-authored by Bill Unruh, who had also produced an important early black hole representation together with Leigh Palmer and Maurice Pryce.[87] Then in 1988, Luminet's paper was cited in an article in *Publications of the Astronomical Society of Japan*.[88] Jun Fukue and Takushi Yokoyama's "Color Photographs of an Accretion Disk Around a Black Hole" presented visualizations from simulations of black hole accretion disks under different observing conditions. Fukue and Yokoyama's paper contained the first depictions of a black hole accretion disk in color. These later visualizations were generated digitally, rather than by hand as Luminet had done. But Fukue and Yokoyama's paper, and later articles on black hole visualizations in peer-reviewed literature would still often be structured similarly to Luminet's paper, starting with a focus on the point of view and then moving on to the black hole images. Some of them would use similar terminology, such as describing visual representations of the surroundings of black holes as "photographs," the observer as a "photographer," or "[a]ssuming that the observer takes a camera with him."[89]

85. Brandon Carter, "Theory of Black Holes with Accretion Disks," *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 368, no. 1732 (1979): 23–25; Daniel Gerbal and Didier Pelat, "Profile of a Line Emitted by an Accretion Disk-influence of the Geometry upon its Shape Parameters," *Astronomy and Astrophysics* 95 (1981): 18–23.

86. Subrahmanyan Chandrasekhar, *The Mathematical Theory of Black Holes* (Oxford: Oxford University Press, Oxford, 1983).

87. Richard Matzner, Tony Rothman, and Bill Unruh, "Grand Illusions: Further Conversations on the Edge of Spacetime," in *Frontiers of Modern Physics: New Perspectives on Cosmology, Relativity, Black Holes, and Extraterrestrial Intelligence*, ed. Tony Rothman (New York: Dover Publications, 1985), 49–81.

88. Fukue and Yokoyama, "Color Photographs of an Accretion Disk around a Black Hole" (n. 26).

89. E.g., Fukue and Yokoyama, "Color Photographs of an Accretion Disk Around a Black Hole" (n.26); Jean-Alain Marck, "Short-Cut Method of Solution of Geodesic Equations for Schwarzchild Black Hole," *Classical and Quantum Gravity* 13, no. 3 (1996): 393–402, 395.

The most prominent case where Luminet's way of imaging a black hole accretion disk was *not* followed is perhaps a later case in science fiction: that of the black hole Gargantua in Christopher Nolan's 2014 film *Interstellar*.[90] The external view of Gargantua was constructed through a collaboration between the theoretical physicist and Nobel Laureate Kip Thorne and the company Double Negative Visual Effects. Shortly after the release of the film, Thorne published a book, *The Science of Interstellar*, presenting the scientific basis for the film, including that of visualizing a black hole, to a general audience.[91] He also co-authored a scholarly article detailing the production of the visualization of Gargantua. The authors cited Luminet's 1979 paper in this description of the "first Hollywood movie to attempt depicting a black hole as it would actually be seen by somebody nearby."[92] Luminet, in turn, showed interest in the visualization of Gargantua. In a preprint article released on ArXiv with the pointed title, "The Warped Science of *Interstellar*," Luminet compared the appearance of the accretion disk in his drawing (figure 2) with that of Gargantua, and noted that "basic visual effects were obviously missing."[93] In particular, Luminet described his surprise at seeing that the black hole accretion disk in *Interstellar* appeared to look symmetrical, unlike his own visualization where the light looked asymmetrical (brighter on the left than on the right) as it took into account more physical effects.[94] Luminet here returned to the phrasing of a "realistic" image. As he had shown in his 1979 paper, he wrote, "a realistic image must show a strong asymmetry of the disk's brightness, so that one side is far brighter and the other is far dimmer."[95] Luminet reported in the paper that Thorne had e-mailed Luminet to explain why these aspects of black hole visualization had been neglected: the film director requested it because "a general audience would have been totally baffled by

90. "Gargantua" was also the name of a black hole in a 1994 book by Thorne targeting a general audience (Kip Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* [London: Norton, 1994], 40). Like Penrose and Luminet, Thorne made references to Escher's work in his communication of black holes (*Black Holes and Time Warps*, 404).

91. Thorne, *The Science of Interstellar* (n.13).

92. James et al., "Gravitational Lensing by Spinning Black Holes in Astrophysics, and in the Movie *Interstellar*" (n.2), 1. Luminet's 1979 paper was also cited in Thorne, *The Science of Interstellar* (n.13).

93. Jean-Pierre Luminet, "The Warped Science of *Interstellar*," ArXiv preprint:arXiv*:1503.08305* (2015, accessed 21 Oct 2022), 7.

94. Ibid., 8.

95. Ibid.

what they are looking at."[96] These effects, Luminet wrote, were therefore dropped. Luminet used the visual effects occurring in the space around a black hole as one of the ways he could communicate their nature. Yet in the context of a science fiction film (with travels through wormholes, strange planets, and communication through a tesseract), the space around a black hole was made to look *less* accurate. The space around a black hole was deemed too peculiar for beholders to make sense of.

"The Warped Science of *Interstellar*" not only dealt with fiction but also referred to the endeavor to produce an actual observation with the Event Horizon Telescope.[97] In a 2014 review of the use of computational simulations in astrophysical research, cosmology, and relativity, Luminet went into more detail. Describing early visualizations from simulations of black holes, Luminet commented that "[a]t the time, black hole imagery was done mainly for pedagogical purpose."[98] Luminet did not specify what he meant by "pedagogical." One of the articles that he referred to was his 1979 paper in *Astronomy & Astrophysics*. The other was an article by Jean-Alain Marck in the journal *Classical and Quantum Gravity*, which included snapshots from multiple angles and distances to a black hole.[99] Possibly, Luminet understood the visualization as a way to further understanding of black holes. His reference to "pedagogy" could also be tied to visualizations in popular science articles and a documentary by Carter, Luminet, and Marck.[100] Although it is not the focus of the present paper, we should note that from the early history of black hole imaging, we see overlap between the use of images in popularization and peer-reviewed publications: the same images were used to communicate similar messages, regardless of the status of a publication as a popularizing or peer-reviewed academic outlet.

Luminet still shows great interest in black hole imaging, and frequently comments on the Event Horizon Telescope in articles, presentations, and blog

96. Ibid.

97. Ibid., 6.

98. Luminet, "From Black Holes to Cosmology" (n.17), 5.

99. Marck, "Short-Cut Method of Solution of Geodesic Equations for Schwarzchild Black Hole" (n.90).

100. Carter and Luminet, "Les Trous Noirs" (n.20), Jean-Alain Marck and Jean-Pierre Luminet, "Plongeon dans un Trou Noir," *Pour la Science* (1997): 50–56. The documentary *Infinitely Curved* was a 1994 film directed by Laure Delesalle and co-written by Luminet and Marc Lachize-Rey. The simulation by Marck used in *Infinitely Curved* can be seen on Luminet's Youtube channel www.youtube.com/watch?v=5Oqop5oltrM (accessed 21 Oct 2022).

posts.[101] He had in fact learned of the Event Horizon Telescope only through reading about the project in *Scientific American*.[102] This indicates a disciplinary and institutional divide. But at the end of his 1979 paper, Luminet in one sentence mentioned that the supermassive black hole in the M87 galaxy could potentially look similar to the image he had made. It was the shadow of this black hole that appeared in the first black hole image based on observation (figure 1), released forty years after Luminet's paper.

On April 10, 2019, six papers were released in a special issue about the observation of the shadow of M87*. Five of the six papers cited Luminet's 1979 paper.[103] They also cited other peer-reviewed papers containing images of the surroundings of black holes. One was by James M. Bardeen, a 1973 paper that aimed to show the "apparent shape" of a black hole.[104] This shape was depicted in a schematic style and looked somewhat like a D-shaped circle. Inspired by Bardeen's paper, Heino Falcke argued that what he called the "shadow" of a black hole could be observed from Earth, using multiple telescopes.[105] A 2000 paper by Falcke, Fulvio Melia, and Eric Agol was important for convincing the astronomical community that the goal of observing a black hole shadow could be possible.[106] Falcke, Melia, and Agol visualized the shadow of a black hole in a simulation as though seen from telescopes, with a depression of light against an orange background. Common to all these papers was that they contained images showing what the authors thought the surroundings of black holes would look like.

101. See for example Luminet, "From Black Holes to Cosmology" (n.17), Jean-Pierre Luminet, "Seeing Black Holes: from the Computer to the Telescope," ArXiv preprint:arXiv*:1804.03909* (2018, accessed 21 Oct 2022); "40 years of Black Hole Imaging (3): from Kerr Black Holes to EHT," e-LUMINESCIENCES (2019). https://blogs.futura-sciences.com/e-luminet/2019/06/12/40-years-of-black-hole-imaging-3-from-kerr-black-holes-to-eht (accessed 21 Oct 2022); "Black Hole Imaging" (n.4); "An Illustrated History of Black Hole Imaging: Personal Recollections (1972–2002)," ArXiv preprint: *arXiv:1902.11196* (2019, accessed 21 Oct 2022).

102. Luminet, "Black Hole Imaging" (n.4). For the *Scientific American* article, see Avery E. Broderick and Abraham Loeb, "Portrait of a Black Hole," *Scientific American* 301, no. 6 (2009): 42–49.

103. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 1"; "First M87 Event Horizon Telescope Results. 2"; "First M87 Event Horizon Telescope Results. 4."; "First M87 Event Horizon Telescope Results. 5"; "First M87 Event Horizon Telescope Results. 6" (all in n.14).

104. Bardeen, "Timelike and Null Geodesics in the Kerr Metric" (n.2).

105. Heino Falcke and Jörg Römer, *Light in the Darkness: Black Holes, the Universe, and Us* (San Fransisco: HarperCollins, 2021), especially 157.

106. Heino Falcke, Fulvio Melia, and Eric Agol, "Viewing the Shadow of the Black Hole at the Galactic Center," *The Astrophysical Journal Letters* 528, no. 1 (2000): L13–L16.

These images were, as part of their reception, perceived as predictions of various aspects of the image shown in figure 1. Acknowledging credit (for instance by citing papers predicting results of observations that were later performed), of course, plays an important role in peer-reviewed literature. In astrophysics, a sentence will typically present a claim, and the first publication credited with making this claim will be cited. In the articles released by the Event Horizon Telescope Collaboration, together with the image shown in figure 1, the authors cited Luminet for features of black hole images. For example, in paper 1, "simulations of Luminet (1979) showed that for a black hole embedded in a geometrically thin, optically thick accretion disk, the photon capture radius would appear to a distant observer as a thin emission ring inside a lensed image of the accretion disk."[107] In paper 2, the authors referenced Luminet's peer-reviewed article by noting how a bright ring around a black hole was "first imaged through simulations by Luminet 1979."[108] In paper 6, Luminet and Falcke, Melia, and Agol were cited together in a description of "a bright ring of emission surrounding a dark interior black hole 'shadow' (Luminet 1979; Falcke et al. 2000)."[109] While it is Luminet's peer-reviewed *paper* that is cited, this paper was in fact solely about an image: how it was produced, what it showed, and why. In other words, predictions in science can be presented in the form of images as well as words or numbers. This is not only interesting in light of research on images of science, but also discussions on simulations in the philosophy of science. Simulations are often framed as being between theory and experiment and observation, but the role of images made on the basis of simulations has not taken as central a focus in discussions of questions such as this.[110] Following up on this philosophical discussion, it is

107. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 1" (n.14), 2.

108. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 2" (n.14), 2.

109. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 6" (n.14), 1.

110. See Christine L. Borgman, *Big Data, Little Data, No Data: Scholarship in the Networked World* (Cambridge, MA: MIT Press, 2015); Peter Galison, "Computer Simulation and the Trading Zone," In *The Disunity of Science: Boundaries, Contexts, and Power*, ed. Peter Galison and David Stump (Stanford, CA: Stanford University Press, 1996), 118–157; Galison, *Image and Logic* (n.6), xix; Stephen Hartmann, "The World as a Process: Simulation in the Natural and Social Sciences," in *Modelling and Simulation in the Social Sciences from the Philosophy of Science Point of View,* ed. Rainer Hegselmann, Ulrich Mueller, Klaus G. Troitzsch (Dordrecht; London: Kluwer Academic, 1996), 77–100 and references cited therein. For a critical review, see Roman Frigg and

interesting to consider the specific practices tied to the use of simulations in fields like astrophysics, including how they are used in relation to observations. Here we have shown how an image based on a simulation informed by theory was, as part of its reception, interpreted as a prediction for what was later observed. Semiotician Maria Giulia Dondero has argued that Luminet's depiction (figure 2) should be seen as a visualization of the possibility of the existence of black holes.[111] We have noted in this paper that Luminet did indeed aim to promote belief in the existence of black holes with his image. The image came to play subtly different roles throughout the history of its use and reception. When it came to the reception of the image, Luminet's drawing became more than the visualization of what was possible. It was treated as one of several early visual predictions of what the surroundings of a black hole looked like.

CONCLUSION

Physicists and astrophysicists have visualized how light near a black hole would appear half a century before the release of the iconic 2019 image (figure 1). A focus on movements of light close to black holes played a key role in expressing the nature of what was otherwise invisible. But interpreting and communicating this region of spacetime, so unlike any other, was a challenge. Martin Kemp, a specialist in perspective, has argued that visual representations can only fall short of representing curved spaces in an intuitive way.[112] Arguing against this, Aaron Sidney Wright has shown how Roger Penrose drew some of his diagrams in perspective as one of the ways these paper tools helped promote

Julian Reiss: "The Philosophy of Simulation: Hot New Issues or Same Old Stew?" *Synthese* 169, no. 3 (2011): 593–613.

111. Maria Giulia Dondero, "Sémiotique de l'Image Scientifique," in *Cartographie de la Sémiotique Actuelle/Mapping Current Semiotics*, vol. 1, ed. Pierluigi Basso Fossali, Jean-François Bordron, Maria Giulia Dondero, Jean-Marie Klinkenberg, François Provenzano, and Gian Maria Tore (Presses Universitaires de Liège–Sciences humaines, 2010), 111–175, 150. See also Maria Giulia Dondero, "Les Images Anachroniques de l'Histoire de l'Univers," *Espressione/Contenuto: Rivista dell'Associazione Italiana di Studi Semiotici, AISS Associazione Italiana di Studi Semiotici* 20 (2007): 1–20; "L'Image Scientifique: de la Visualisation à la Mathématisation et Retour," *Nouveaux Actes Sémiotiques* (2009): 1–20; and Maria Giulia Dondero and Jacques Fontanille, *The Semiotic Challenge of Scientific Images: A Test Case for Visual Meaning* (New York: Legas Publishing, 2014).

112. Kemp, *Seen/Unseen* (n.37), 82.

intuition among researchers and students working with GR.[113] We would largely agree with Wright's view. We should note that some black hole researchers *did* view images of their object of study as counter-intuitive. Alain Riazuelo, for example, produced influential visualizations of a Kerr black hole without an accretion disk, and he noted how they showcased "the most counter-intuitive effects."[114] Yet black hole imaging, as we have shown in this paper, was still used to promote intuition about black holes. By depicting the spatial relation between observer and object of observation in a very precise way, even specifying the exact angle of observation, Luminet showed how the observer could see the entire accretion disk despite not moving—as if the observer were able to simultaneously look at the black hole from several angles. Luminet's aim was not to confound beholders or to remind them of their active role as a beholder, as is common in visual illusions known from the arts. He used apparent "optical distortions" arising with the behavior of light surrounding an invisible object to *further* intuition, not to confound.

Like Penrose, Luminet was inspired by the work of M. C. Escher, and as we have noted, this influenced the creation of Luminet's drawing. But the drawing did not represent "impossible worlds" like some of Escher's artworks.[115] Instead, both in his peer-reviewed 1979 paper and later comments, Luminet stressed that his image was "realistic." He emphasized primarily that his simulation on which the drawing was based took into account "realistic physical properties of the accretion disk."[116] Luminet also described his drawing, which he had carefully made with black ink and stippling, as a "simulated photograph."[117] The result was a compelling application of chiaroscuro, with a strong contrast between light and darkness revealing light surrounding the region from which no light can escape.

113. Wright, "The Advantages of Bringing Infinity to a Finite Place"; "The Origins of Penrose Diagrams in Physics, Art, and the Psychology of Perception, 1958–62" (both in n.38).

114. Alain Riazuelo, "Seeing Relativity-I: Ray Tracing in a Schwarzschild Metric to Explore the Maximal Analytic Extension of the Metric and Making a Proper Rendering of the Stars," *International Journal of Modern Physics D* 28, no. 02 (2019): 1950042, 1. See also Alain Riazuelo, "Seeing Relativity-II: Revisiting and Visualizing the Reissner–Nordström Metric," *International Journal of Modern Physics D* 28, no. 06 (2019): 1950084; "Seeing Relativity—III. Journeying within the Kerr Metric toward the Negative Gravity Region," *International Journal of Modern Physics D* 29, no. 16 (2020): 2050109.

115. See Gombrich, *Art and Illusion* (n.40), 206, for this description of Escher's work.

116. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 231.

117. Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk" (n.2), 228.

Luminet did include brief references to telescopic observation, but visualizations from simulations of what the shadow of a black hole would look like if observed using telescopes came decades later.[118] Luminet, however, did mention the black hole candidate in the galaxy M87 as potentially looking similar to his image. It was the shadow of M87* that was first observed and imaged by the Event Horizon Telescope. Peer-reviewed papers focused on visual representations of black holes based on calculations or simulations were cited in five of the six publications released on April 10, 2019, together with the image shown in figure 1.[119] David Kaiser has argued that Feynman diagrams stayed in use in part because of the associations to realism some physicists had.[120] Luminet's image was not only described as "realistic" by Luminet and others, but as part of its reception it came to be treated as one of the visual predictions of various characteristic aspects of images such as that shown in figure 1.

Whereas in peer-reviewed papers, "realistic" qualities of images were emphasized, and images were presented as predictions in the forms of images, in the science fiction film *Interstellar*, some of the effects shown by Luminet were neglected. Even for a film focused on a voyage through a wormhole, communicating through dimensions, and creating a world without distinction between up and down, the space around a black hole was seen as too strange to present to audiences. Decades after images such as Luminet's drawing were used to communicate black holes, visualizations of the surroundings of black holes still present a challenge to beholders.

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118. See Falcke, Melia, and Agol, "Viewing the Shadow of the Black Hole at the Galactic Center" (n.106).

119. Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. 1"; "First M87 Event Horizon Telescope Results. 2"; "First M87 Event Horizon Telescope Results. 4."; "First M87 Event Horizon Telescope Results. 5"; "First M87 Event Horizon Telescope Results. 6" (all in n.14).

120. Kaiser, *Drawing Theories Apart* (n.6).

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